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# From P&ID to DBN: Automated HVAC FDD modelling framework using large language models

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**Keywords:** Fault Detection and Diagnosis, Diagnostic Bayesian Network, Large Language Model, Piping and Instrumentation Diagrams, HVAC.

## Extended abstract

Buildings account for approximately 40% of energy consumption in the European Union and over one-third of energy-related greenhouse gas emissions, with a significant portion attributed to heating, ventilation, and air conditioning (HVAC) systems. Effective fault detection and diagnosis (FDD) are essential for reducing energy waste and lowering maintenance costs in HVAC operations. FDD methods for HVAC systems have been extensively studied and can be broadly classified into two categories: knowledge-based and data-driven approaches. Knowledge-based approaches heavily rely on predefined rules and domain expertise and remain the most widely used in existing HVAC systems. Over the past decade, data-driven FDD approaches have gained popularity. However, data-driven FDD approaches require high-quality labelled fault datasets for model training, which can be time-consuming and costly to obtain. To address this challenge, various studies have explored the use of generative adversarial networks (GANs) and other data augmentation techniques to synthesize realistic fault data and improve model performance. Despite these advancements, challenges related to generalization, scalability, and the interpretability of black-box models remain key concerns in the adoption of data-driven FDD approaches.

Diagnostic Bayesian networks (DBNs), as probabilistic graphical models, present a promising solution for HVAC FDD, providing several advantages such as robustness to uncertainties, modelling flexibility, scalability, and interpretability (Lu *et al.*, 2024). DBNs have been successfully applied to FDD for individual HVAC components as well as aggregated systems and whole building systems (Wang *et al.*, 2024a, 2024b; Mosteiro-Romero *et al.*, 2024). More systematically, Taal *et al.* (2018, 2020a, 2020b, 2020c) proposed the four symptoms and three faults (4S3F) reference architecture, which establishes a structured approach to HVAC FDD by linking system design in piping and instrumentation diagrams (P&IDs) with DBN modelling. However, constructing DBNs for HVAC systems involves several challenges in practice. One of the primary difficulties is that the current DBN development process is either a tedious and time-consuming manual task or heavily dependent on training data, much like data-driven approaches, which poses significant barriers to the widespread adoption of DBNs in HVAC FDD applications.

Recent advancements in large language models (LLMs) present new opportunities to overcome these barriers in DBN modelling for HVAC FDD. On the one hand, LLMs, pre-trained on large-scale real-world data, exhibit a strong ability to understand and apply domain knowledge, including key concepts in HVAC systems and FDD (Lu *et al*, 2024). On the other hand, LLMs have demonstrated powerful code generation, auto-correction, and reasoning capabilities (Zhang *et al.*, 2024). By leveraging these strengths, LLMs have the potential to streamline the traditionally labor-intensive DBN modelling process into automated construction, making FDD solutions more accessible for real-world HVAC applications.

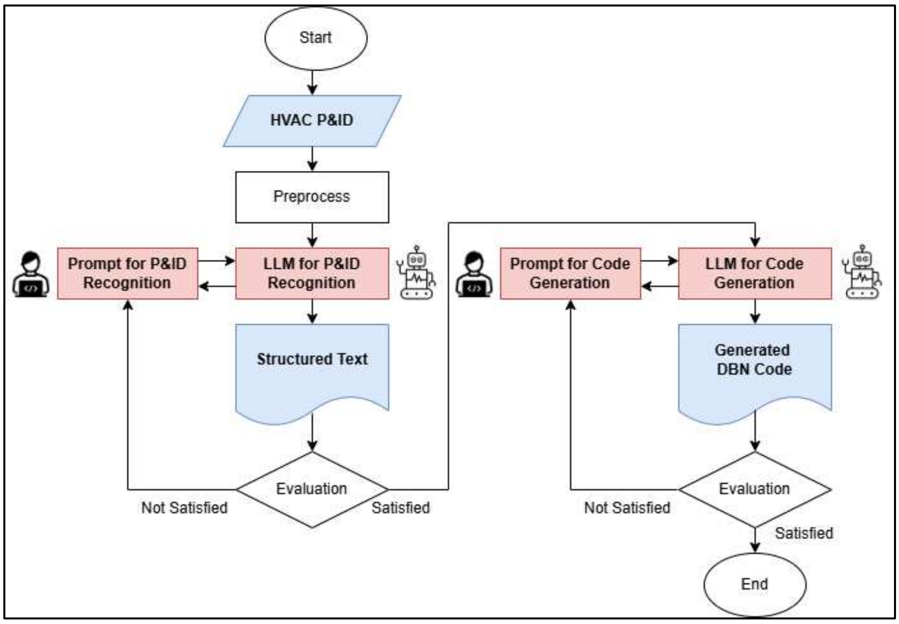


Figure 1. Automated DBN modelling framework for HVAC FDD

We propose a novel automated DBN modelling framework for HVAC FDD that utilizes LLMs to construct DBN from P&ID, shown as Figure 1. The proposed framework consists of two key stages, P&ID digitalization and DBN code generation.

- **Stage 1: LLM-based P&ID Digitalization**
  Many P&IDs exist as static PDFs or images, making automated processing challenging. Traditional P&ID digitalization involves multiple steps, including symbol detection, text extraction, line tracing, and graph reconstruction, which requires extensive training for different P&ID standards and extensive rule-based programming. Our framework utilizes multimodal LLMs (e.g., GPT-4V, Gemini, LLaVA) to simultaneously analyse both textual and visual information, transforming P&IDs into machine-readable formats (structured text) like JSON, IFC, or xgXML.

  Prompt engineering in this stage focuses on selecting the appropriate approach—zero-shot, one-shot, or few-shot prompting—based on the complexity and variability of the P&ID diagrams and the capabilities of the specific LLM employed. To evaluate the effectiveness of LLM-based P&ID digitalization, the assessment focuses on two key aspects: symbol and text recognition accuracy and completeness of the structured output. The first aspect ensures that component labels and system annotations are correctly extracted, minimizing errors in textual interpretation. The second aspect verifies the structural accuracy of the machine-readable output (e.g., JSON, IFC, xgXML), ensuring that all components, connections, and dependencies are accurately identified and properly represented.

- **Stage 2: LLM-based DBN Code Generation**
  Once the P&ID is transformed into structured text, LLMs, guided by carefully designed prompts, infer potential faults and related symptoms, and subsequently generate the corresponding DBN code. This step demands LLMs with strong inference capabilities to accurately interpret system behaviour, and proficient code generation abilities to translate the inferred information into executable DBN code, such as GPT-4o, Claude-sonnet.

  Prompt engineering for this stage focuses on the granularity and scope of the information provided to the LLMs. Key considerations include: 1) only providing the structured text captured from P&ID; 2) incorporating with additional information on the HVAC system's control strategies; 3) adding relevant FDD context, such as the 4S3F reference architecture and the generic modelling procedure for DBNs. Moreover, to further optimize performance, different prompt strategies will be explored, such as Chain of Thought (CoT) prompting. CoT prompting encourages the LLM to break down complex reasoning into smaller, more manageable steps.

  To evaluate the effectiveness of DBN code generalization, the assessment focuses on two key aspects: code examination and FDD performance evaluation. Code Examination ensures the generated DBN adheres to structural and semantic correctness. This includes verifying structural compliance (e.g., proper node definitions, dependency structures) and fault-symptom relationship accuracy, ensuring the inferred dependencies align with known HVAC fault mechanisms. FDD Performance Evaluation assesses the DBN's effectiveness in real-world fault diagnosis. The generated model is tested using fault case data, evaluating its diagnostic accuracy, robustness, and generalization.

The proposed framework aims to streamline the traditionally complex, time-intensive, and labor-intensive process of constructing DBNs, making it more intelligent and efficient. By leveraging LLMs for automated P&ID digitalization and DBN code generation, the framework accelerates model development while reducing manual effort and potential errors. This advancement supports the transformation of the building services industry toward smarter and more efficient operations, ultimately enhancing building performance and enabling seamless integration into large-scale energy systems.

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